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Volumetric 3-D Vector Flow Measurements using a 62+62 Row-Column Addressed Array

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Abstract—Experimental results from volumetric 3-D vector flow measurements using a 62+62 row-column addressed (RCA) array are presented. A plane-by-plane steered transmit sequence and its post processing steps are described for obtaining 3-D vector flow in a volume. A modified version of the transverse oscillation (TO) velocity estimator is used, which exploits the focal lines generated with the tall elements of a RCA array. Validation of the method is made in a flow-rig system where circulating blood mimicking fluid produced a steady parabolic flow profile with a flow rate of 13.7 mL/s, translating to a peak velocity of 24.1 cm/s. A volume rate of 16.4 volumes per second is obtained, and estimated flow rates based on nine steered planes were compared with a corresponding matrix array [6]. The imaging and volumetric power Doppler performance results for both imaging [4] and 3-D vector flow estimation [5] can be translated to a peak velocity $v_0$ via the relation $v_0 = 2Q/(\pi R^2)$.

TABLE I

<table>
<thead>
<tr>
<th>Transducer Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements in x</td>
<td>62</td>
</tr>
<tr>
<td>Number of elements in y</td>
<td>62</td>
</tr>
<tr>
<td>Pitch in x</td>
<td>0.27 mm = 0.53λ</td>
</tr>
<tr>
<td>Pitch in y</td>
<td>0.27 mm = 0.53λ</td>
</tr>
<tr>
<td>Width</td>
<td>0.245 mm</td>
</tr>
<tr>
<td>Kerf</td>
<td>0.025 mm</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>35 MHz</td>
</tr>
<tr>
<td>Center frequency</td>
<td>3.0 MHz</td>
</tr>
<tr>
<td>Footprint size</td>
<td>1.67×1.67 cm²</td>
</tr>
</tbody>
</table>

I. INTRODUCTION

Volumetric B-mode imaging has previously been achieved with fully populated $N \times N$ 2-D matrix arrays. However, the large number of connections in a fully populated matrix array results in a complicated interconnect and a heavy processing task, which hinders a real-time implementation. As an alternative to the fully populated matrix array, the row-column addressed (RCA) 2-D array was suggested [1], [2], [3]. In an RCA array, elements are accessed by either their row or column index, effectively reducing the total number of elements and channels in the interconnect to $2N$.

Despite the significant reduction in element count for a RCA array, probes for experimental use have shown convincing results for both imaging [4] and 3-D vector flow estimation [5]. The imaging and volumetric power Doppler performance of an emulated 2-D RCA array was also lately investigated and compared with a corresponding matrix array [6].

This paper presents 3-D vector flow estimation in a full volume and expands on previous work, where a transmit sequence was designed to acquire 3-D vector flow estimates in a plane using an RCA array [5]. The extra spatial dimension was achieved by redesigning the transmit sequence and modifying the post processing steps. With 3-D vector flow information present in a full volume, new complex blood dynamics can be investigated as well as user dependency can be reduced.

Section II presents the measurement materials and methods applied, section III describes the experimental setup, section IV presents and results, and section V provides conclusions.
A plane-by-plane 3-D volumetric vector flow imaging emission sequence was designed by expanding the single plane approach described in previous work [5]. A schematic illustration of the applied steered transmit sequence is seen in Fig. 1. As described in Section II-C, 2-D vector flow can be obtained in an entire plane from each transmit event. By transmitting $N$ distinguishable steered focused emissions by only exciting row elements and perform TO beamforming on each of the events, results in $N$ planes in a volume containing 2-D vector flow estimates. By interleaving the sequence with $M$ steered focused emissions where only column elements are excited, yields 2-D vector flow information also in the orthogonal dimension. Combining the 2-D vector flow information from the row and column emissions results in volumetric 3-D vector flow in the intersections of the $N$ and $M$ planes as illustrated.
Fig. 2. Volumetric 3-D vector flow obtained in the flow-rig displayed for the nine cross-planes.

in Fig. 1. The repeating volumetric sequence is schematically written as

\[ C_1 \rightarrow C_2 \rightarrow \ldots C_M \rightarrow R_1 \rightarrow R_2 \rightarrow R_3 \rightarrow \ldots R_N \]

where \( C_i \) indicates focal line index \( i \) when emitting with column elements and \( R_i \) similarly for row elements.

The volumetric sequence consisted of \( N = 11 \) row emissions and \( M = 9 \) column emissions and was designed to acquire continuous data. The row emissions were steered from \(-15^\circ\) to \(15^\circ\) in steps of \(3^\circ\) and the column emissions from \(-8^\circ\) to \(8^\circ\) in steps of \(2^\circ\). This produces estimates along the intersections of the \( N \times M = 99 \) planes corresponding to a \(16^\circ \times 30^\circ\) volume. The c-plane at \(3\) cm depth spans an area of \(16.1\) mm \(\times 8.4\) mm.

E. Data processing

The emission sequence was repeated 2240 times corresponding to \(4.3\) seconds of data. The data was beamformed offline on a Linux cluster using a delay-and-sum beamformer specialized for RCA arrays [8]. Velocities were estimated with averaging over 32 estimates yielding 70 independent velocity estimates for each point using the TO method.

The nine scan-planes corresponding to cross-sections of the vessel are extracted for volume flow estimation. Volume flow is calculated by integrating the angle corrected estimates across each cross-sectional plane. The bias with respect to the flow rate reported by the flow rig and standard deviations are calculated for the volume flow through each scan plane.

III. EXPERIMENTAL SETUP

With the described probe and scanner a measurement was performed with the volumetric 3-D emission sequence. The applied transmit frequency was \(3.0\) MHz and the pulse repetition frequency \( (f_{prf}) \) was \(10.5\) kHz. For the continuous data acquisition sequence presented here with \( M + N = 20 \) emissions and averaging over 32 estimates, \(16.4\) independent 3-D vector flow volumes per volume are attained.

The flow rate chosen in this setup was \(13.7\) mL s\(^{-1}\), translating to a peak velocity of \(24.1\) cm s\(^{-1}\). The center of the vessel was located \(2.9\) cm from the transducer’s surface.

IV. RESULTS

A volumetric representation of the mean out-of-plane velocity estimates are shown in Fig. 2. Based on the velocity component perpendicular to the cross-sectional area, the mean flow rate for each plane was calculated and are shown in Fig. 3. A positive bias was found for all of the steering angles, with the smallest at \(2^\circ\) (\(6.5\) \%) and the largest at \(-8^\circ\) (\(21.2\) \%). Similarly, the smallest standard deviation was found for the plane steered by \(8^\circ\) (\(\pm 3.0\) \%) and the largest standard deviation was at a steering of \(0^\circ\) (\(\pm 3.8\) \%). The overall mean flow rate, based on the estimated value for each plane was \(15.2\) \pm \(0.7\) mL s\(^{-1}\). However, erroneous velocities are estimated at larger steering angles, which may be due to the chosen lateral wavelength not matching the expected velocity range or that a further optimization of the beamforming for steered directions are required.

An illustration of the present parabolic flow is seen in Fig. 4, where the mean out-of-plane velocity component for the nine cross-sectional scan planes are shown. As expected, similar
Fig. 3. Estimated flow rates for each of the nine steered planes with the expected flow rate (dotted line) and standard deviation of the estimates denoted by the blue bar around the mean velocity estimate (red dot).

Fig. 4. Mean out-of-plane velocity for the 9 cross-sectional planes steered from $-8^\circ$ to $8^\circ$ in steps of $2^\circ$ averaged from 70 frames.

profiles with similar peak-velocities are seen across all steering angles.

V. CONCLUSION

This work demonstrates that volumetric 3-D vector flow can be measured with a 2-D RCA array with only 124 channels at a volume rate of 16.4 volumes per second. Measurements in a flow rig with laminar, parabolic flow yield a precision better than 4% and a bias below 21.2% in a sector of $16^\circ \times 30^\circ$.

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REFERENCES